Light QCD exotics at BESIII

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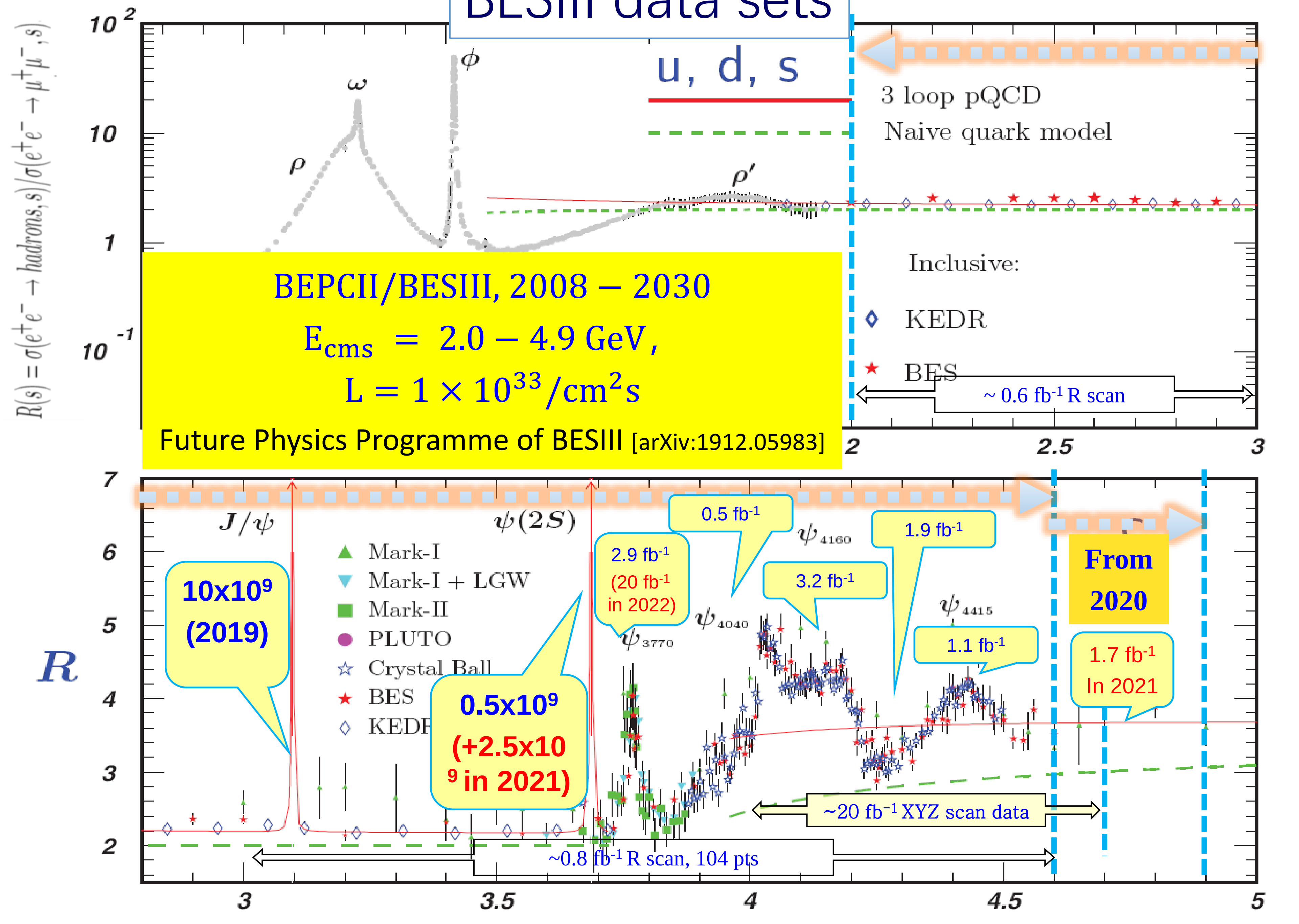
on behalf of BESIII

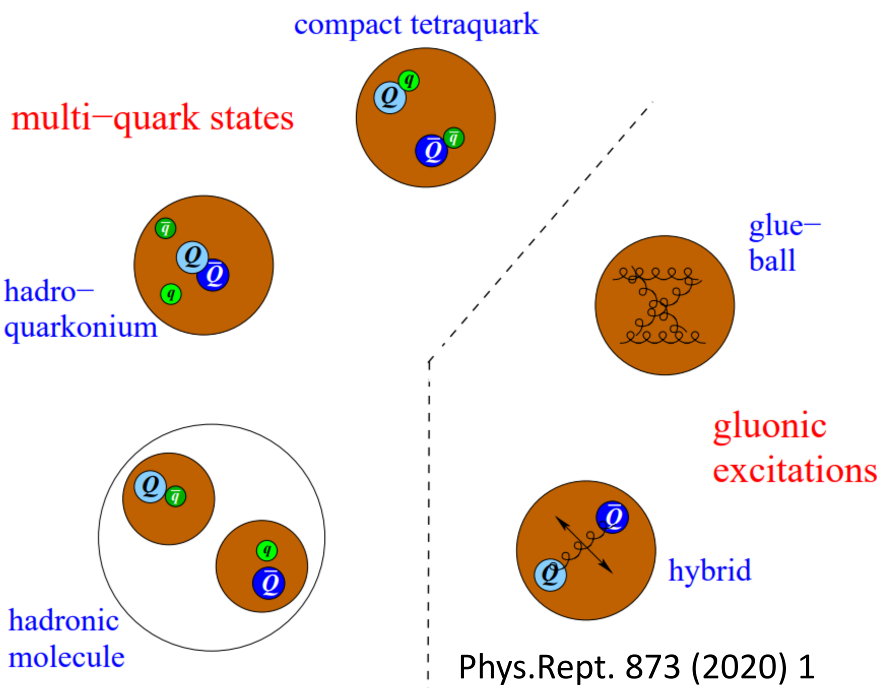
Workshop of Light-Quark Exotic Hadrons, Snowmass Hadron Spectroscopy group

September 30, 2020

BESIII data sets

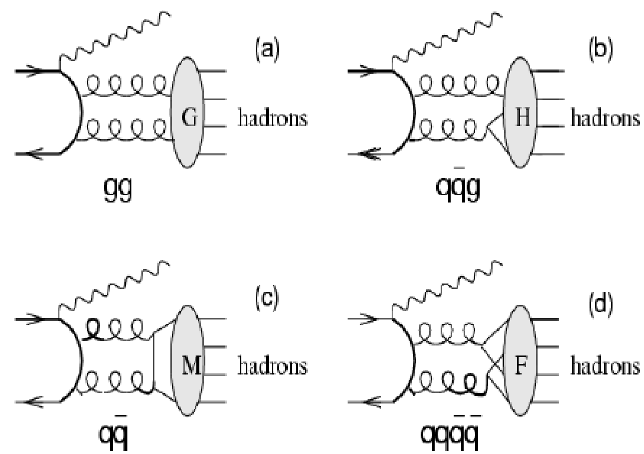


Charmonium decays provide an ideal lab for light hadron physics



Phys.Rept. 873 (2020) 1

- Clean high statistics data samples
- Well defined initial and final states
  - Kinematic constraints
  - I(J^{PC}) filter
- “Gluon-rich” process



$$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$$

$$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$$

What’s the role of gluonic excitation and how does it connect to the confinement?

A few highlights

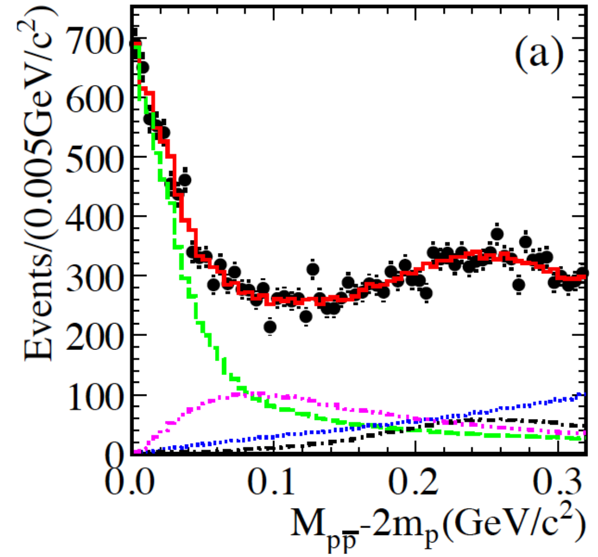
- Structures near $N\bar{N}$ threshold
  - $X(p\bar{p})$ and X(1835)
- Scalars near $K\bar{K}$ threshold
  - $a_0(980) - f_0(980)$ mixing

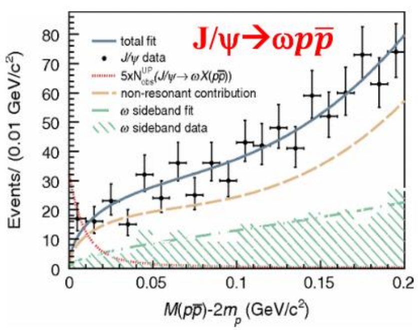
- Search for glueballs and hybrids

$p\bar{p}$ threshold enhancement $X(p\bar{p})$

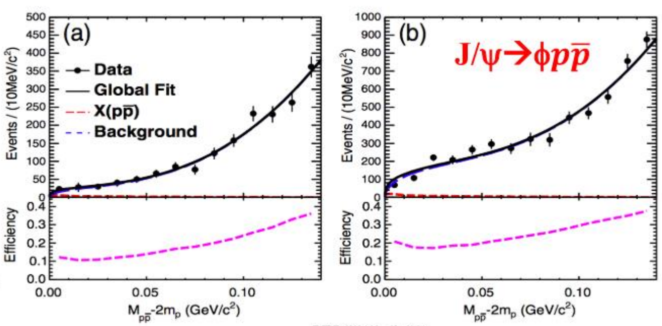
- First observed in $J/\psi \to \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \to \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure
- Non-observation in hadronic decays: not from pure FSI of $p\bar{p}$

PRL 108 112003

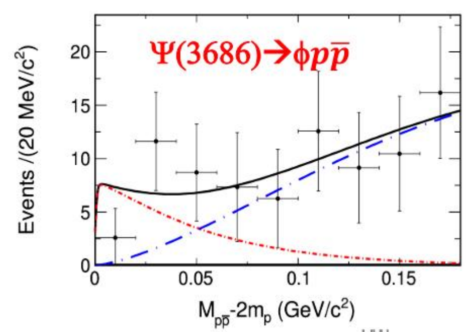




PR D87 112014



PR D93 052010

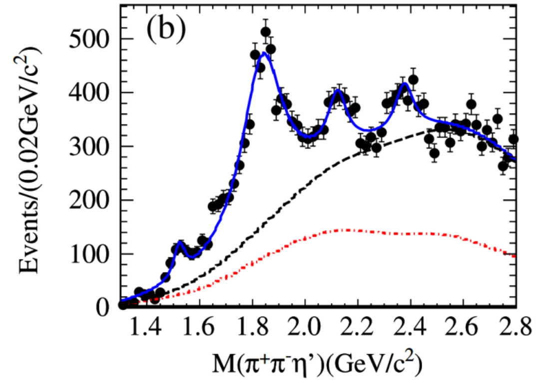


PR D99 112010

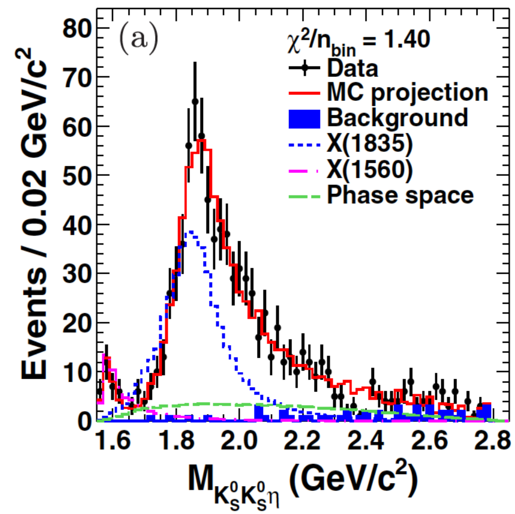
X(1835)

- Observed by BESII in $J/\psi \to \gamma\eta'\pi^+\pi^-$, confirmed at BESIII
- PWA of $J/\psi \to \gamma K_s K_s \eta$
  - $X(1835) \to K_S K_S \eta$ is observed (the $K_S K_S$ system is dominantly produced through the $f_0(980)$)
  - $J^{PC}=0^{-+}$
- Observation of $\eta(1475)$ and X(1835) in $J/\psi \to \gamma\gamma\phi$
  - Flavor filter: sizeable $s\bar{s}$ component

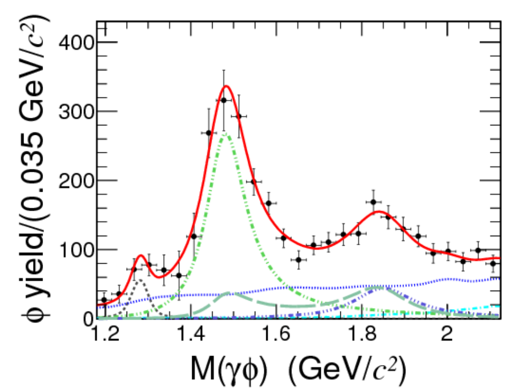
PRL 106 072002



PRL 115 091803



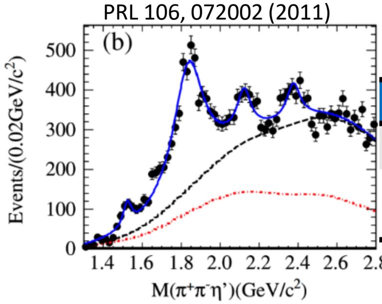
PRD 97 051101



Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between X(1835) and X($p\bar{p}$)

X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

PRL 106, 072002 (2011)



X(1835) $J^{PC}=0^{-+}$

$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2

$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

X($p\bar{p}$) $J^{PC}=0^{-+}$

$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2

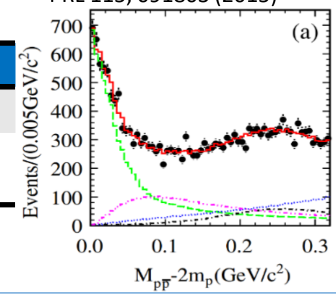
$\Gamma = 13 \pm 19$ MeV/c^2

(< 76 MeV/c^2 @ 90% C.L.)

X($p\bar{p}$) observed in $J/\psi \to \gamma p\bar{p}$

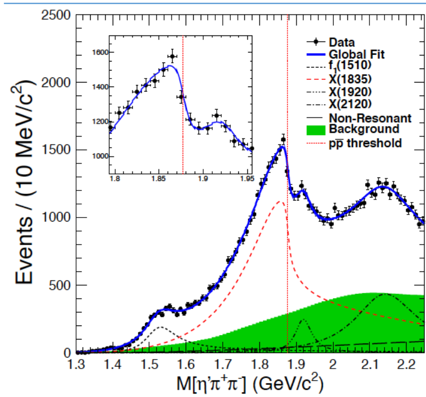
PRL 108, 112003 (2012)

PRL 115, 091803 (2015)



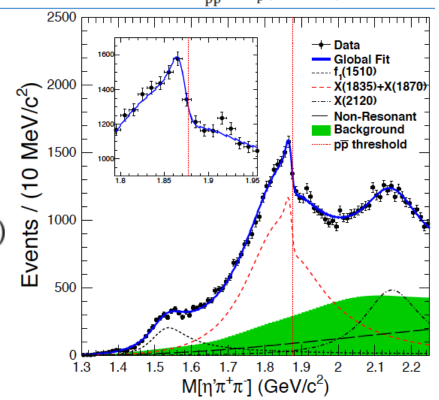
Connection is emerging

PRL 117, 042002 (2016)



Model 1:
Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/c^2

Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c^2



The anomalous line shape can be modeled two models with equally good fit quality

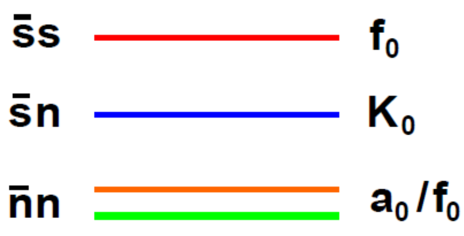
- **Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold**

- Structures near $\mathrm{N\bar{N}}$ threshold
  - $\mathrm{X(p\bar{p})}$ and X(1835)
- Scalars near $\mathrm{K\bar{K}}$ threshold
  - $\mathrm{a_0(980) - f_0(980)}$ mixing

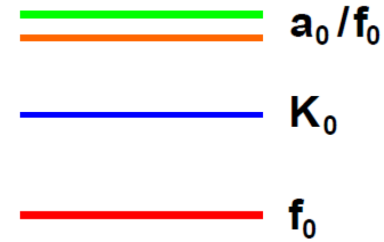
- Search for glueballs and hybrids

$a_0(980) - f_0(980)$ mixing

- The nature of ground state scalar $a_0(980)$ and $f_0(980)$ are controversial



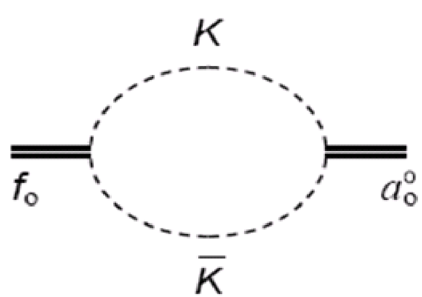
Quark model

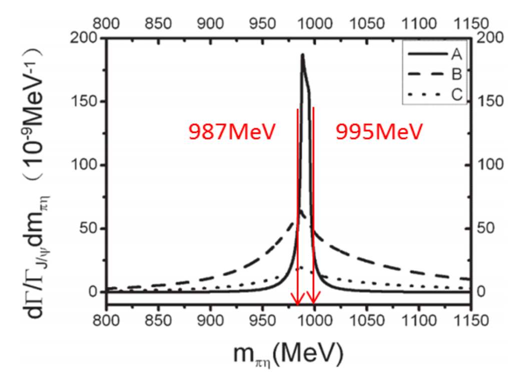


Experimental data

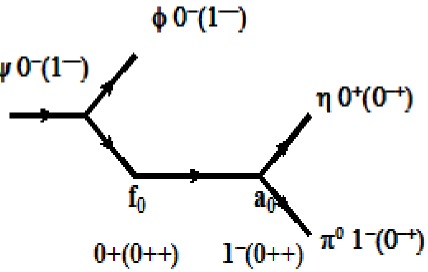
$q\bar{q}$ mesons, $K\bar{K}$ molecules, tetraquarks, hybrids,…?

- $a_0(980) - f_0(980)$ mixing (proposed in 1979) is very sensitive to $K\bar{K}$ coupling, which is an important probe to the internal structure of $a_0(980)$ and $f_0(980)$

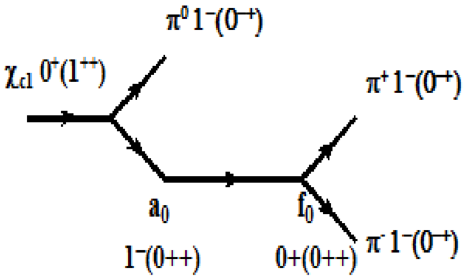




$a_0(980) - f_0(980)$ mixing

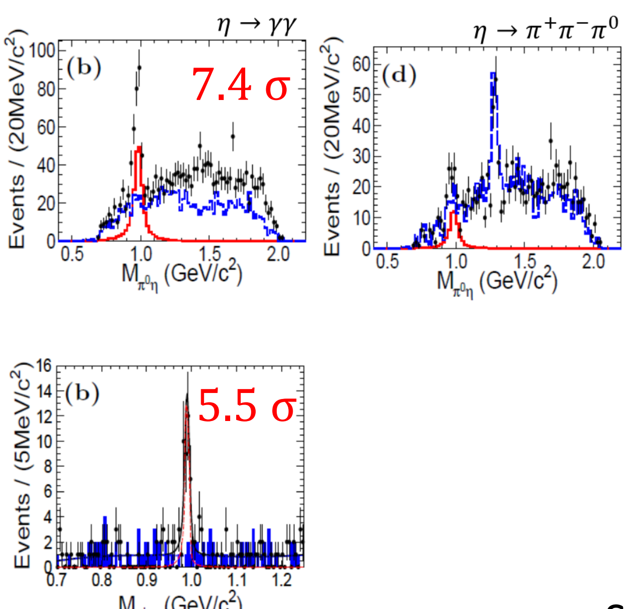


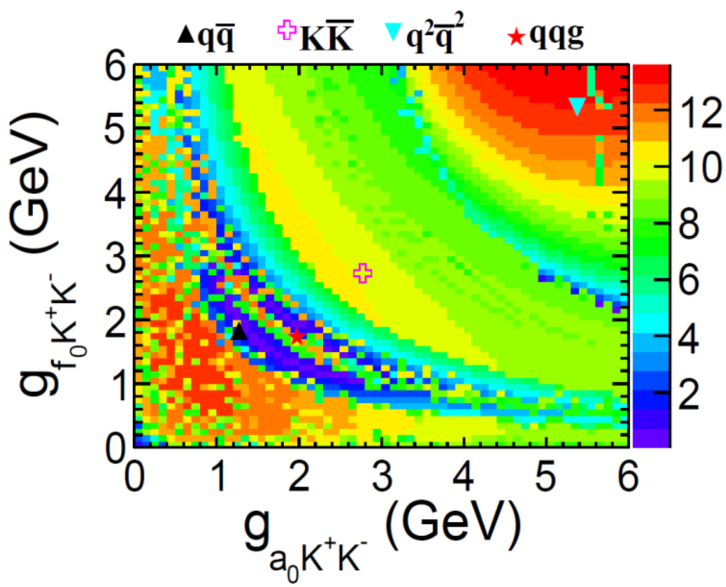
PR D75 114012,
PR D76 074028



PR D78 074017

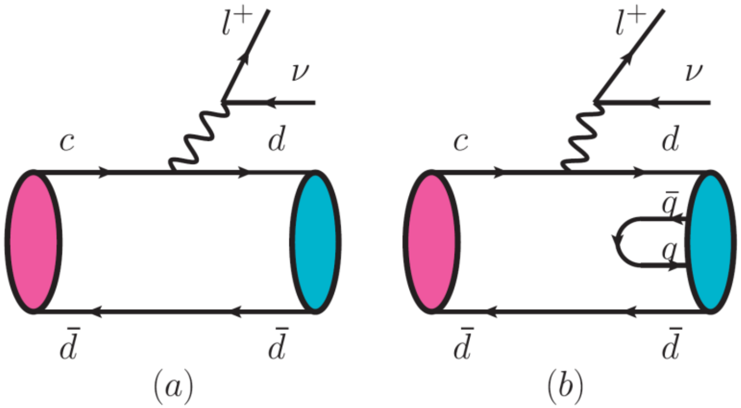
First direct measurement with > 5σ , [BESIII PRL 121 022001]





Significance of $a_0 - f_0$ mixing signal VS. coupling of $a_0(f_0) \to K\bar{K}$

Explore light hadrons with charmed meson decays

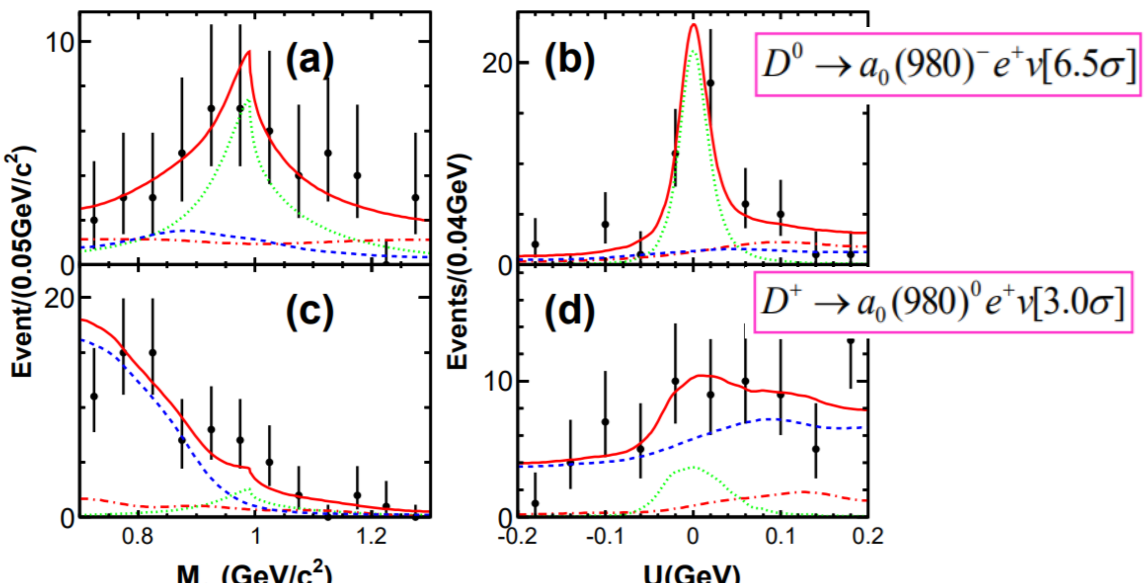


In the SU(3) symmetry limit,

PR D82, 034016 (2010)

$$R = \frac{\mathcal{B}(D^+ \to f_0(980)l^+\nu) + \mathcal{B}(D^+ \to f_0(600)l^+\nu)}{\mathcal{B}(D^+ \to a_0^0(980)l^+\nu)}$$

$$= \begin{cases} 1 & \text{two quark} \\ 3 & \text{tetra-quark} \end{cases}.$$



BESIII measurements:

PRL 121, 081802 (2018)

PRL 122, 062001 (2019)

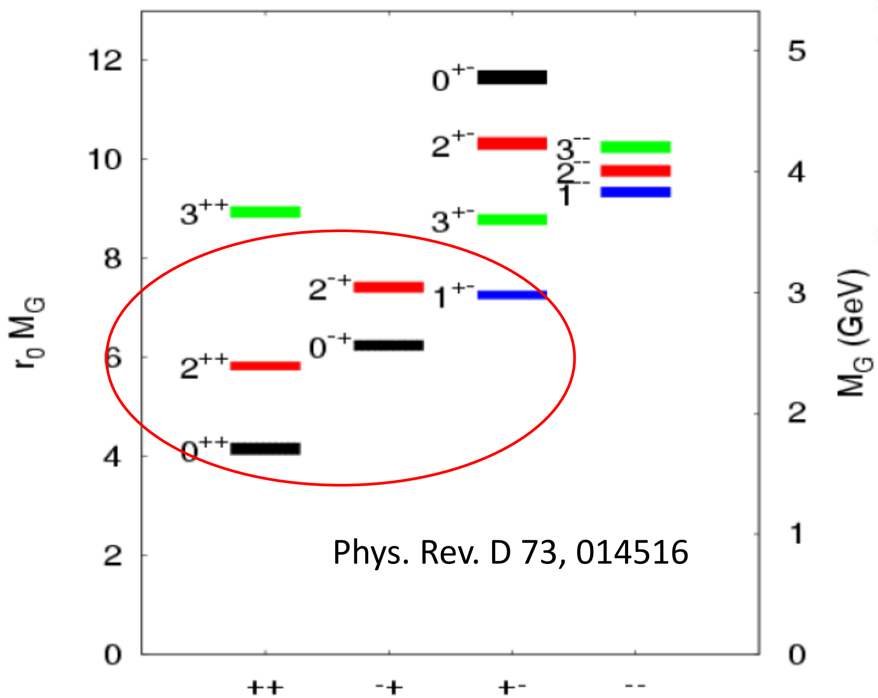
$R_{BESIII} > 2.7$ @ 90% C.L.

- Structures near $\mathrm{N\overline{N}}$ threshold
  - X($\mathrm{p\overline{p}}$) and X(1835)
- Scalars near $\mathrm{K\overline{K}}$ threshold
  - $\mathrm{a_0(980) - f_0(980)}$ mixing

- Search for glueballs and hybrids

Glueball

Evidence of gluon self interaction
Provide critical information on the gluon field and the quantitative understanding of confinement



Glueballs from Lattice simulations in the pure gauge theory without quarks

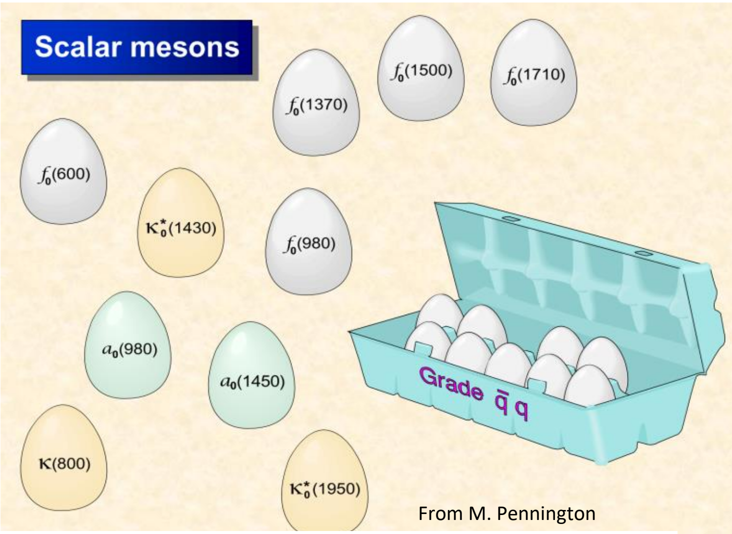
	m_π (MeV)	$m_{0^{++}}$ (MeV)	$m_{2^{++}}$ (MeV)	$m_{0^{-+}}$ (MeV)
$N_f = 2$	938	1417(30)	2363(39)	2573(55)
	650	1498(58)	2384(67)	2585(65)
$N_f = 2+1$ [22]	360	1795(60)	2620(50)	—
quenched [13]	—	1710(50)(80)	2390(30)(120)	2560(35)(120)
quenched [14]	—	1730(50)(80)	2400(25)(120)	2590(40)(130)

Low lying glueballs with ordinary quantum number
→mixing with qqbar mesons

Systematic studies needed

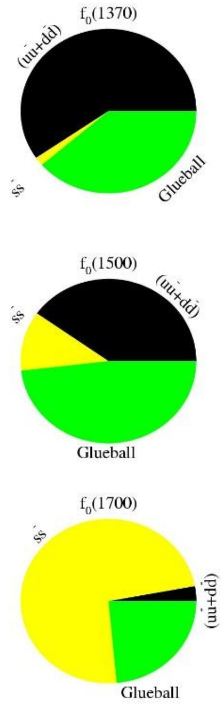
- Outnumbering of simple QM states
- Abnormal properties

Overpopulated scalar mesons



From M. Pennington

Name	Mass [MeV/c^2]	Width [MeV/c^2]
$f_0(600)$ *	400 – 1200	600 – 1000
$f_0(980)$ *	980 ± 10	40 – 100
$f_0(1370)$ *	1200 – 1500	200 – 500
$f_0(1500)$ *	1507 ± 5	109 ± 7
$f_0(1710)$ *	1718 ± 6	137 ± 8
$f_0(1790)$		
$f_0(2020)$	1992 ± 16	442 ± 60
$f_0(2100)$	2103 ± 7	206 ± 15
$f_0(2200)$	2189 ± 13	238 ± 50



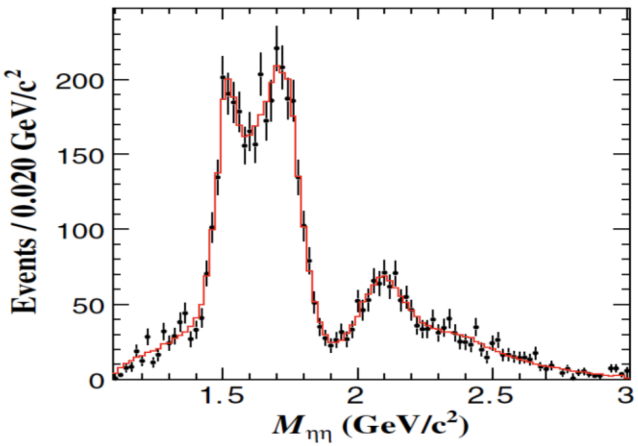
Mixing scheme：

very controversial and model dependent

$f_0(1500)$, $f_0(1710)$, which one has more gluonic component?

Amplitude analysis of $J/\psi \to \gamma\eta\eta/K_S^0 K_S^0$

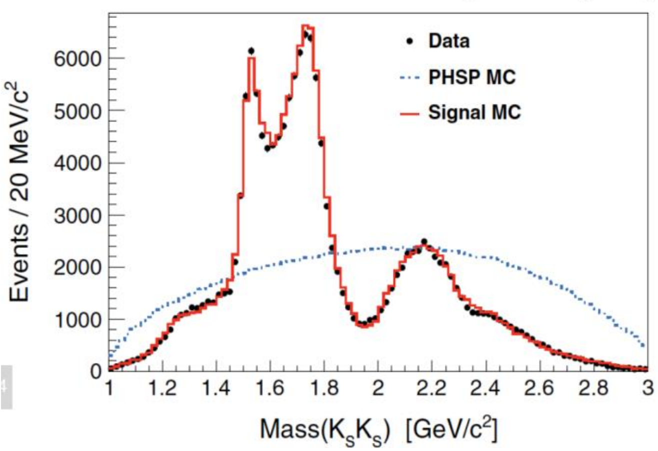
BESIII PRD 87, 092009 (2013)



Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

Br of $f_0(1710)$ ~10x larger than $f_0(1500)$

BESIII PRD 98, 072003 (2018)



Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{[illegible]}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$\cdots$	$349 \pm 18^{+23}_{-1}$	$\cdots$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

Scalar glueball candidate

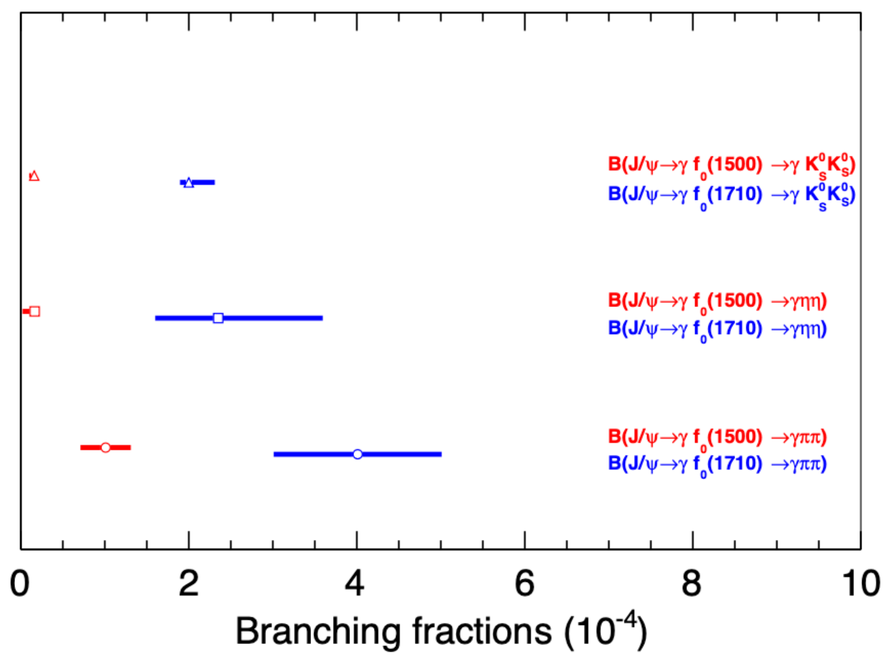
$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha \frac{|p|}{M^2_{J/\psi}} |E_1(0)|^2 = 0.35(8) keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9) \times 10^{-3}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

Experimental results

- B($J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}$)=($8.5^{+1.2}_{-0.9}$) $\times 10^{-4}$
- B($J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi$)=($4.0\pm1.0$)$\times 10^{-4}$
- B($J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega$)=($3.1\pm1.0$)$\times 10^{-4}$
- B($J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta$)=($2.35^{+0.13+1.24}_{-0.11-0.74}$)$\times 10^{-4}$

$\Rightarrow$ B($J/\psi \to \gamma f_0(1710)$) > 1.7×10^{-3}



$f_0(1710)$ largely overlapped with scalar glueball

Tensor glueball candidate

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22) keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

Experimental results

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$$

Phys.Rev. D87, 092009 (2013)

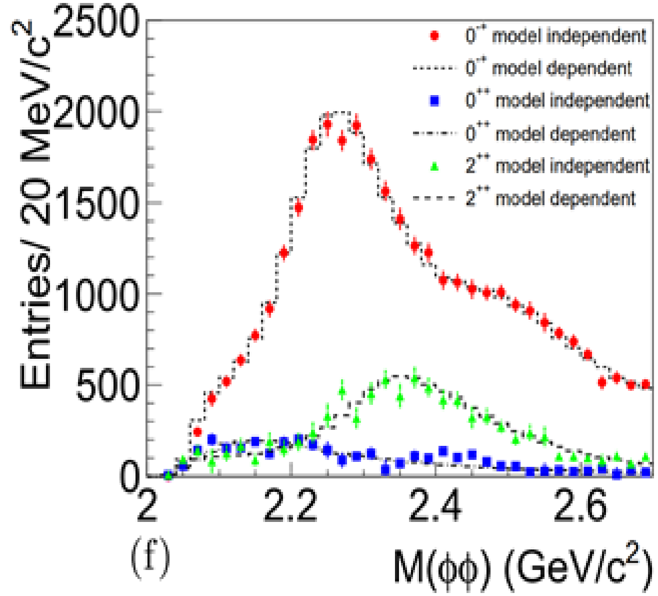
$$Br(J/\psi \to f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

Phys.Rev. D93, 112011 (2016)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_S K_S) = (5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$$

Phys.Rev. D98, 072003 (2018)

BESIII $J/\psi \to \gamma\phi\phi$



(f)

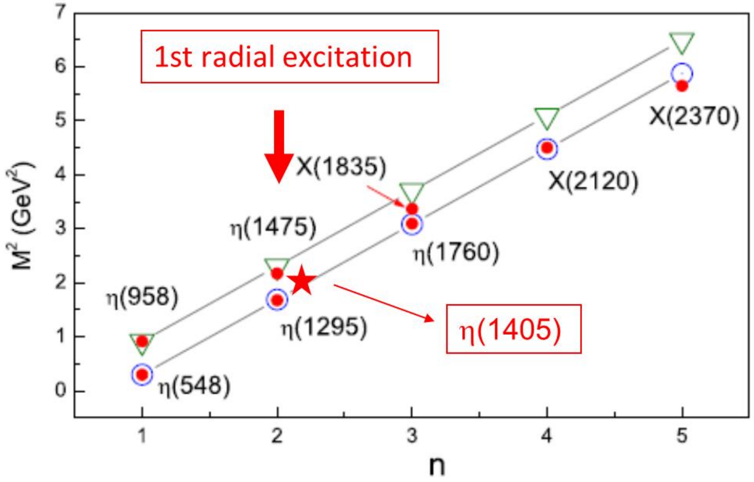
$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$

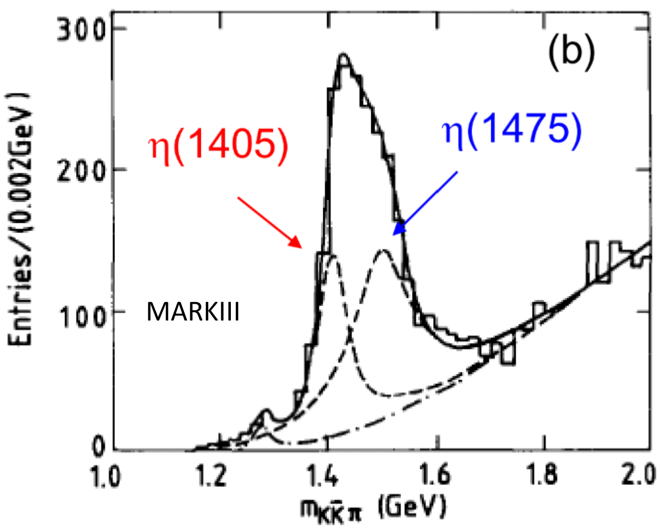
Consist with central exclusive production in WA102

It is desirable to search for more decay modes

Pseudoscalar glueball

The small number of expected pseudoscalars in the quark model provide a clean and promising environment for the search of glueballs





Where is the 0^{-+} glueball

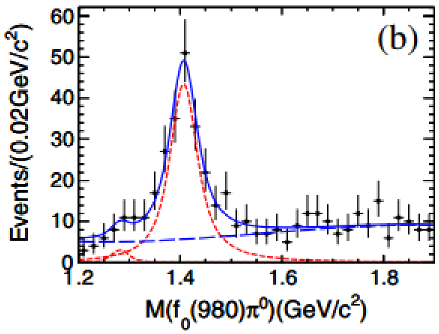
- LQCD: 0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- What's the nature of the outnumbered $\eta(1405)$?

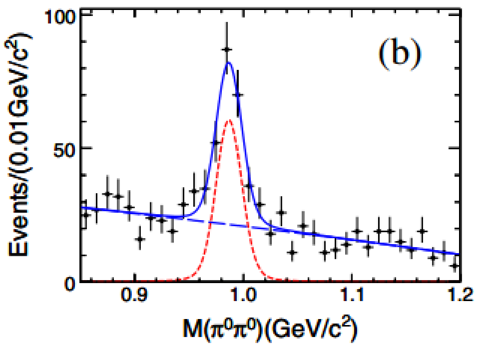
Long standing E-ι puzzle

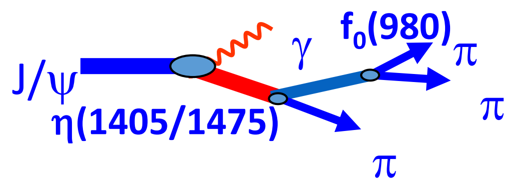
$$M = 1416 \pm 8^{+7}_{-5};\ \Gamma = 91^{+67}_{-31-38}{}^{+15}\ \mathrm{MeV}/c^2$$

$$M = 1490^{+14+3}_{-8-6};\ \Gamma = 54^{+37+13}_{-21-24}\ \mathrm{MeV}/c^2$$

Isospin-violating decay of $\eta(1405) \to f_0(980)\pi^0$







BESIII PRL 108 182001

f0(980) is extremely narrow: $\Gamma \cong 10$ MeV.

PDG: Γ(f0(980)) $\cong$ 40~100 MeV.

Anomalously large isospin violation:

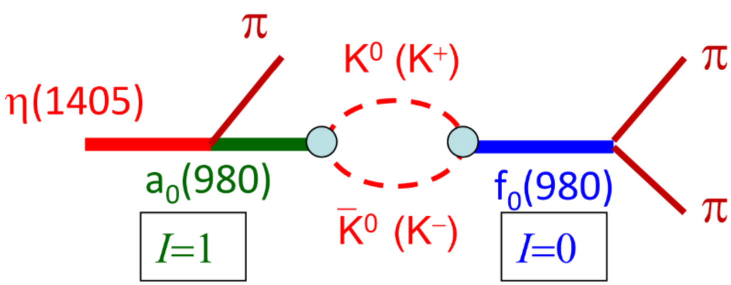
$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

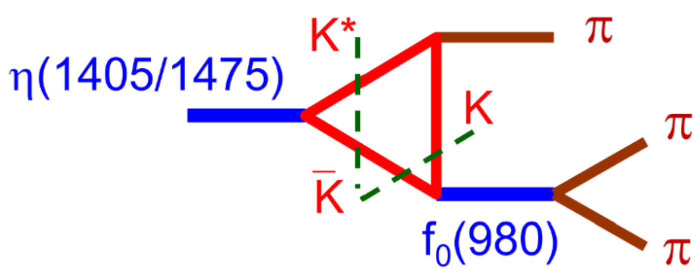
$$\xi_{af} = \frac{Br(\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \to a_0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\%(90\%\ C.L.)$$

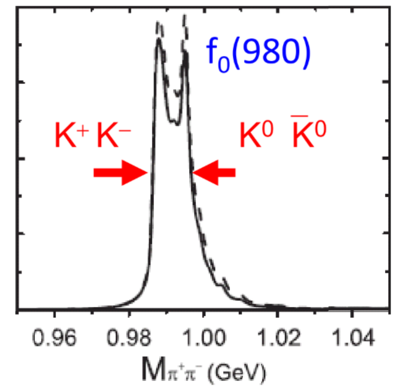
PRD, 83(2100)032003

Isospin-violating decay of $\eta(1405) \to f_0(980)\pi^0$

Inspired by BESIII's observation, the triangle singularity mechanism plays an important role in the study of threshold phenomena







→No need for two pseudoscalars around 1.4 GeV

→Look for pseudoscalar glueball in higher mass region

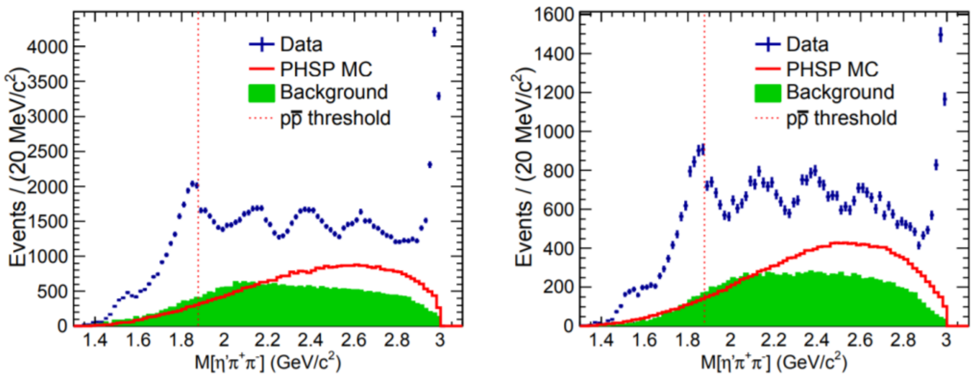
Manifestations of TS in various processes

Phys.Rev.Lett. 108 (2012) 081803
Phys.Rev. D86 (2012) 114007
Phys.Rev. D88 (2013) 014045
Phys.Rev. D87 (2013) 014023
Phys.Rev. D89 (2014), 054038
Phys.Rev. D92 (2015) 034010
Phys.Rev. D91 (2015) 094022
Phys.Rev. D92 (2015) 036003
Phys.Lett. B753 (2016) 297
Phys.Rev. D93 (2016) 114027
Phys.Rev. D95 (2017) 034015
Phys.Rev. D97 (2018) 096002

Structures >2 GeV

$J/\psi \to \gamma\eta'\pi^+\pi^-$

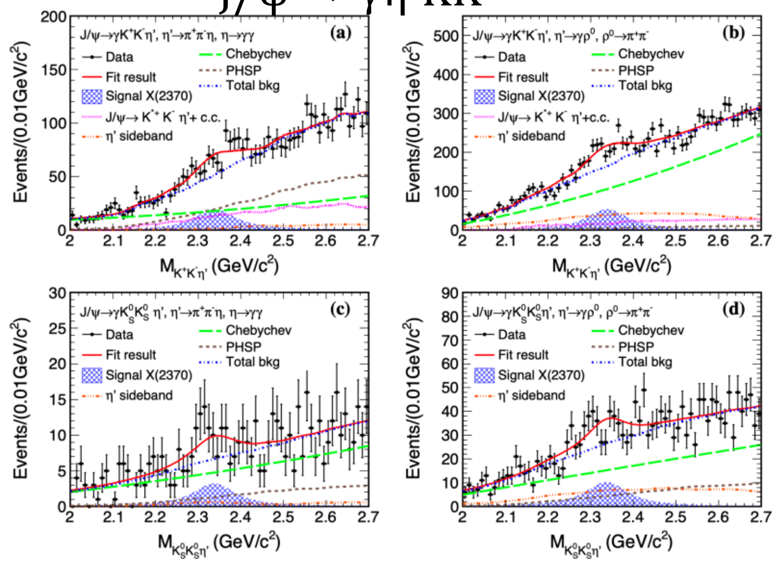
BESIII PRL 106, 072002, PRL 117, 042002



X(2370)

$J/\psi \to \gamma\eta' KK$

BESIII Eur.Phys.J.C 80 (2020) 8, 746



8.3σ

Landscape of light glueball has been updated

Scalar: Overpopulation

- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

✓ **Strong production of $f_0(1710)/f_0(2100)$ in $J/\psi \to \gamma\, \eta\eta/KK/\pi\pi$**

Tensor: large uncertainty

- LQCD: 2^{++}(2.3~2.4 GeV)

✓ **Strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/KK/\pi\pi/\phi\phi$**

Pseudoscalar: very little known above 2 GeV, puzzles in low mass region

- LQCD: 0^{-+}(2.3~2.6 GeV)

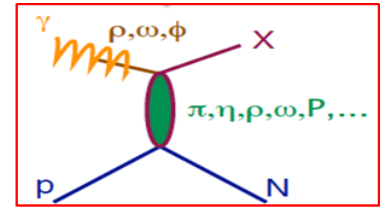
✓ **Trajectory**:
  - **η(1405) /η(1475) can be one resonance**

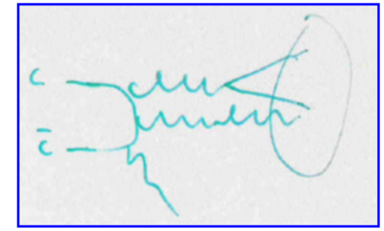
☐ **Above 2 GeV: X(2370)?**

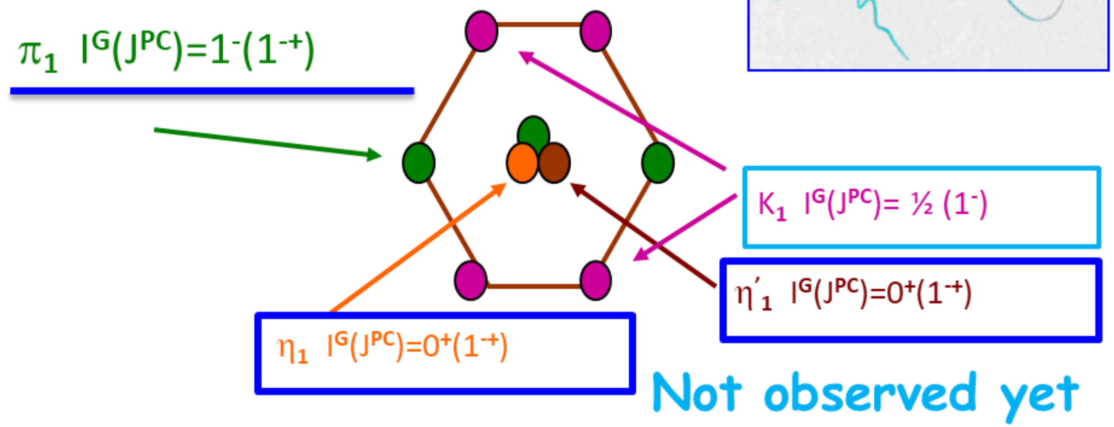
Hybrids

GlueX@JLab

BESIII





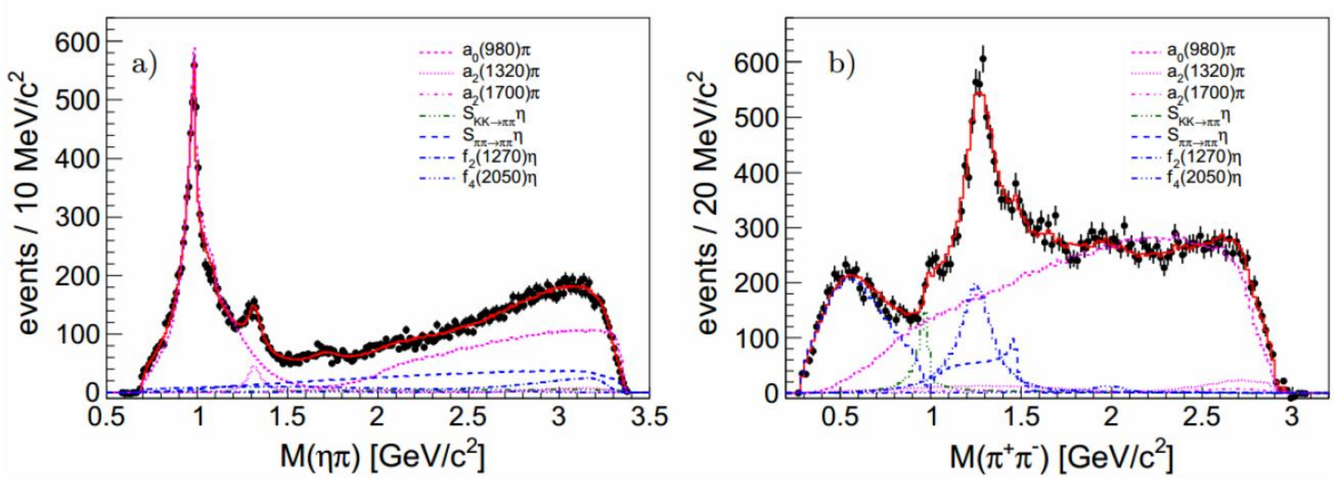


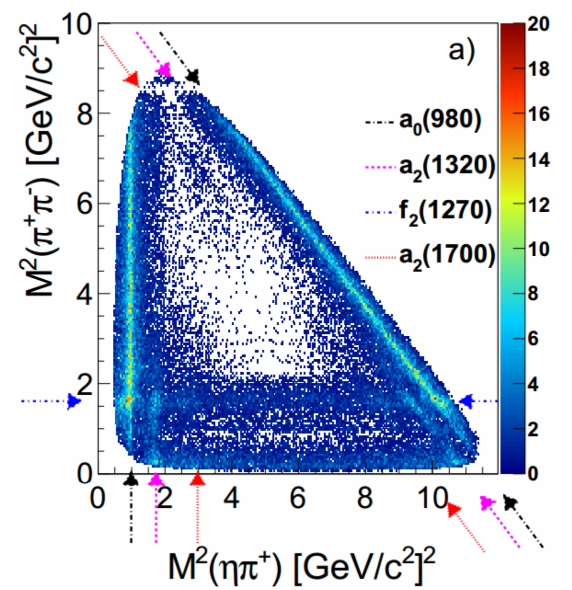
- Only π_1 are observed. Isoscalar 1^{-+} is critical to establish the nonet
- Isoscalar 1^{-+} is expected to be produced in J/ψ radiative decays
  - $J/\psi \to \gamma + a_1\pi/\eta f_1/K_1K/\eta\eta'/\eta f_2\ /\ldots,$
- Synergies between other experiments with different production mechanism

Hybrids

- χ_{c1} **provides another suitable environment to look for 1^{-+}**
  - $\boldsymbol{\pi_1}$**(1600) studied in** $\boldsymbol{\chi_{c1} \to \eta'\pi^+\pi^-}$ **by CLEO-c** [PRD 84 112009(2011)]
  - **only** $\boldsymbol{\pi_1}$**(1400) has been reported decays to** $\boldsymbol{\eta\pi}$

$\chi_{c1} \to \eta\pi^+\pi^-$ BESIII PR D95, 032002(2017)





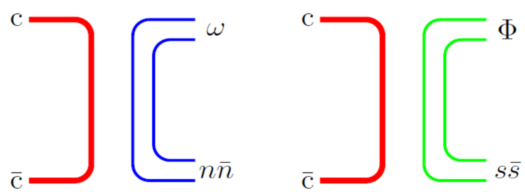
- **Clear evidence for a$_2$(1700) in χ_{c1}decays.**
- **First measurement of** $g'_{\eta'\pi} \neq 0$ **using** $a_0(980) \to \eta\pi$ **line shape.**
- **Measured upper limits for** $\pi_1(1^{-+})$ **in 1.4 - 2.0 GeV/c^2 region.**

10B J/ψ and 3B ψ’ provide great opportunities

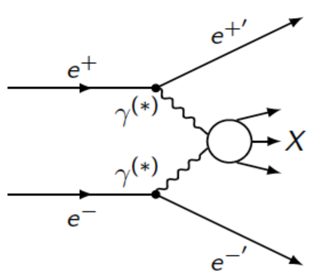
	0^+	2^+	0^-
J/ψ→γPP			
J/ψ→γVV			
J/ψ→γPPP			
J/ψ→γPPPP			

Flavor Filters：

J/ψ→γX →γ γ V　　J/ψ→ω/ϕ + X



Anti filter:



- 0^+, 2^+ : coupled channel analysis
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory >2 GeV, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V
- 1^{-+}
  - J/ψ→$\gamma\eta_1^{(\prime)}$
  - $\chi_{c1} \to \eta\eta_1^{(\prime)}, \pi\pi_1$

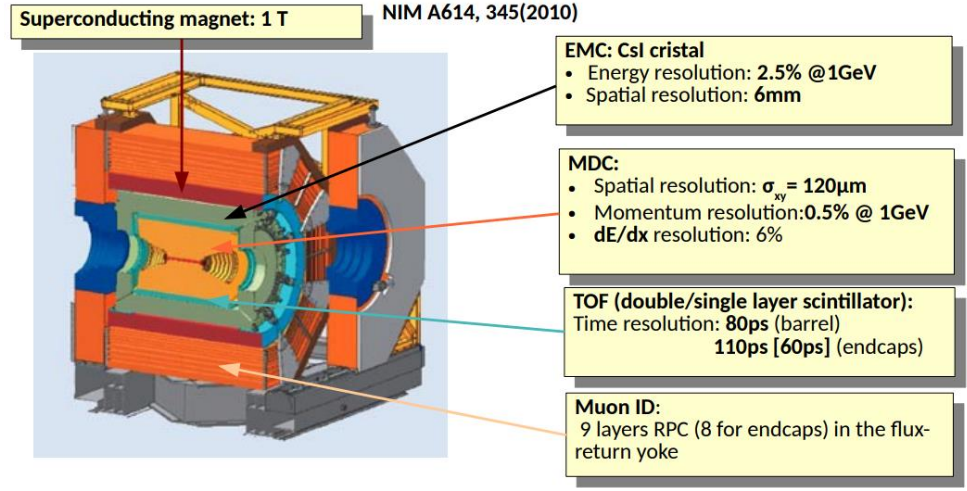
- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study light exotics

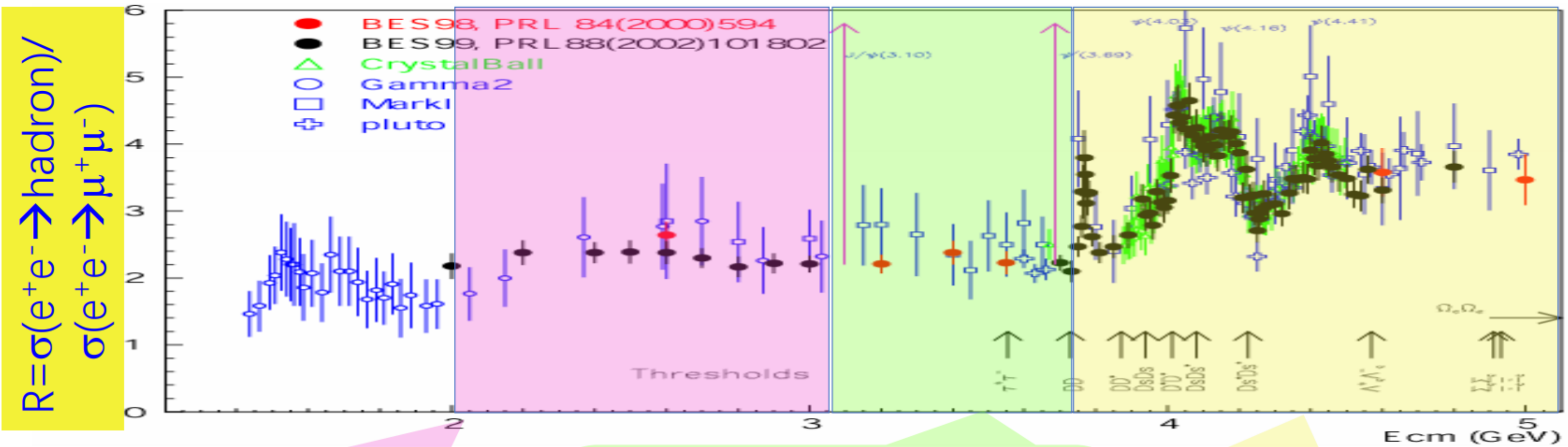
- To obtain a complete picture, different experiments with complementary information are needed

- To explore the high statistics data sets, more advanced tools and closer experiment<->theory cooperation are needed

Thank you for your attention

Physics at BESIII



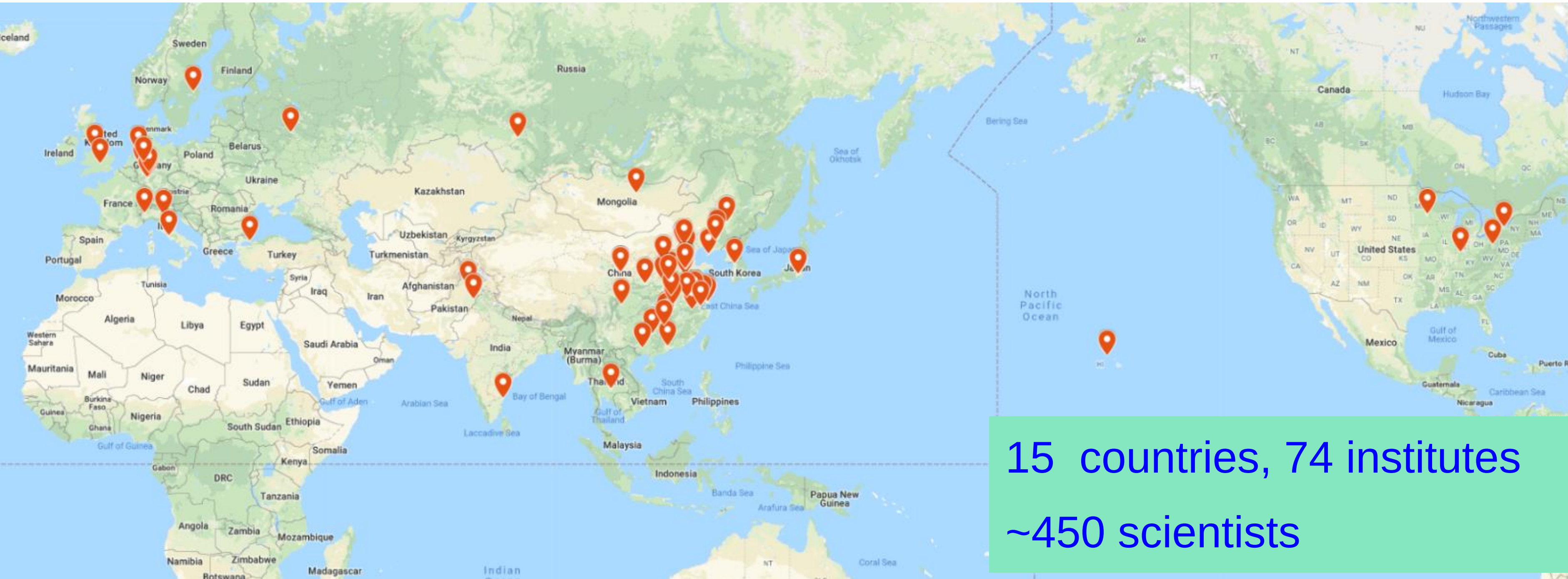


- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-$\bar{D}_0$ mixing
- Charm baryons

BESIII collaboration



15 countries, 74 institutes

~450 scientists